Mode Processing and Tomography for the Philippine Sea Experiment

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LONG-TERM GOALS

This project is a three-year basic research effort on deep water ocean acoustics. The broad goals of this research are to understand mode scattering in the deep water channel, to characterize deep ocean noise processes, and to implement acoustic tomography using the low mode signals.

OBJECTIVES

There are three major technical objectives of the proposed research. The first objective is to analyze the spatial characteristics of noise in the deep ocean using measurements from the distributed vertical line array (DVLA). The second objective is to measure mode statistics for the Philippine Sea environment. Note that the DVLA deployed with the PhilSea experiment is designed to resolve the low modes excited by the moored sources. In addition to improving fundamental understanding of signal and noise processes in the deep ocean, the results of the first two research objectives will provide valuable information for signal processing performance predictions. The third objective is to implement tomographic inversions using the Philippine Sea data set. The Philippine Sea experiment is a great opportunity for mode tomography because of the capabilities of the DVLA and the shorter source ranges (as compared to previous experiments). In addition to exploring the standard ("active") acoustic tomography using the controlled sources deployed as a part of the experiment, this project will investigate passive acoustic tomography using ambient noise sources.

APPROACH

The primary focus of this three-year effort is the ONR-sponsored Philippine Sea experiment, including the Pilot Study in 2009 and the full experiment in 2010-2011. The principal investigator (PI) for this effort is Professor Kathleen Wage of George Mason University (GMU). The graduate research assistant on the project is Mr. Mehdi Farrokhrooz. The PI collaborates with members of the North Pacific Acoustic Laboratory (NPAL) group on the experimental aspects of this work, specifically the investigators at Scripps Institution of Oceanography (SIO). During 2009-2010 she was on sabbatical at

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SIO working with Dr. Peter Worcester and his group.

There are three primary starting points for this research. The first is the 2010-2011 Philippine Sea experiment, which will facilitate measurement of mode fluctuation statistics. Kathleen Wage worked with Peter Worcester to select the deep vertical line array hydrophone depths for accurate mode filtering. The design process built on the work that the PI has done for previous deep water propagation experiments (ATOC, NPAL, SPICE/LOAPEX), *e.g.*, [9, 10]. Once the design was complete, work has focused on adapting and expanding the tools for estimating broadband mode signals from vertical line array data. In 2010, an analysis was done to examine the robustness of mode filtering algorithms to inaccuracies in sensor positions.

One objective of this project is to analyze deep ocean ambient noise. The starting point for this work is to implement an analysis of the vertical directionality of the noise measurements made with the axial and deep subarrays during the PhilSea09 pilot study. Since the SPICE04 experiment also included axial and deep arrays, this data set is also being analyzed for comparison with the PhilSea results.

The third starting point for the project concerns ambient noise tomography, which contributes to the third research objective. This idea builds on work done using deep water noise measurements made during the SPICE04 experiment. Although noise measurements were not the primary focus of SPICE04, the experiment provided a large data set of low frequency measurements made with a 40-element vertical line array. The basic idea is that ambient noise can be represented as a sum of uncorrelated acoustic modes, which is a reasonable assumption for distant sources, *e.g.*, see the work of Kuperman and Ingenito on noise modeling [7]. In this case the eigenvectors of the noise covariance matrix for a vertical line array should correspond to the sampled modeshapes. While other authors have investigated using an eigendecomposition of the noise covariance to to estimate the mode functions, *e.g.*, [12, 6, 8, 2], few deep water experiments have employed the mode-resolving arrays needed to implement this approach. An initial analysis of the empirical modes derived from the SPICE04 data set was implemented with previous ONR funding (Award N00014-05-1-0639). As a part of this project, the analysis is being extended to answer some outstanding research questions.

WORK COMPLETED

Since the inception of the grant in March 2009, work has been completed in seven areas, as described below.

Vertical Array Design for the 2010-2011 Experiment: Design calculations were implemented to determine the sensor spacing that would provide the best resolution of the acoustic modes in the Philippine Sea environment. Results of this work were presented at the Underwater Acoustic Measurements Conference in Nafplion, Greece in July 2009 and during the experimental planning session at the NPAL Workshop in September 2009. Additional calculations were done in late 2009 to finalize the design.

Philippine Sea Experimental Work: The PI participated in the deployment cruise for the 2009 Philippine Sea Pilot Study. She also participated in the deployment cruise in 2010 and the recovery cruise in 2011 for the year-long Philippine Sea Experiment. While at Scripps prior to the 2010 cruise, she tested the noise response and frequency response of 168 hydrophone modules. During the 2010 deployment cruise she and Lora Van Uffelen did a live broadcast from the R/V Revelle to the ASA meeting in Baltimore as a part of an outreach effort to the Girl Scouts (sponsored by ASA's Women in Acoustics Committee).

PhilSea Noise Analysis: Spatial spectral analysis of the ambient noise recorded during the PhilSea09 Pilot Study was implemented. Results were obtained for both the axial and deep subarrays. Analysis of the 2009 Pilot Study noise data was presented at the Acoustical Society of America meetings in April and November 2010 [3, 11]. After the DVLA for the 2010-2011 experiment was recovered in April 2011, an initial spectral analysis of the year-long time series was completed. The results of this analysis were reported at the Ocean Acoustics review meeting at Stennis Space Center in May 2011.

SPICE04 Noise Analysis: In 2010-2011 spatial spectral analysis of the SPICE04 data was implemented. GMU PhD student Mehdi Farrokhrooz is currently analyzing the vertical directionality of the noise received on the SPICE arrays. Initial results of this work were presented at the NPAL Workshop in October 2010. New results, including an investigation of the effect of array tilt on directionality estimates, were presented at the Acoustical Society of America Meeting [4].

Empirical Mode Analysis of the SPICE04 Noise Data Set: The spatial spectral analysis of the SPICE04 data set revealed that cable strum is responsible for the poor performance of algorithms that estimate deep water modeshapes using an empirical mode decomposition of the noise correlation matrix. Work is ongoing to evaluate the impact of array tilt on the modeshape estimates.

Mode Processing: In 2009-2010 the PI analyzed the robustness of standard mode processing algorithms to mismatch due to array element localization errors.

NPAL Workshop October 2010: PI Kathleen Wage was the local arrangements chair for the 13th annual North Pacific Acoustic Laboratory Workshop held at Airlie Center in Warrenton, Virginia.

RESULTS

The following paragraphs summarize the key FY11 results obtained from the initial noise analysis of the PhilSea 2010-2011 data set. The data used in this analysis is a subset of the DVLA data set consisting of 487 receptions. The DVLA spanned the water column with 150 hydrophones. The hydrophone modules performed exceptionally well in 2010-2011.

The 487 receptions were processed as follows to obtain the temporal and spatial noise spectra. Each tomography reception was 155 seconds long. Temporal spectra were estimated using block-averaged transforms based on 2-second windows, for a resolution of approximately 0.5 Hz. The frequency-wavenumber spectra were then computed using conventional beamforming. A Hanning window was used to taper both the temporal and spatial transforms.

Figure 1 shows the minimum and median temporal spectra for center hydrophone of the five subarrays. These statistics were computed using 152 receptions that contained no tomography source signal. The median curve for the shallowest subarray is substantially higher for frequencies below 60 Hz. At least part of the increase is due to the significantly louder contamination from cable strum observed on the uppermost array. The median spectra show a decrease in noise power with depth, for frequencies below 300 Hz; between 300 and 500 Hz, the median levels for the 5 subarrays are almost identical. The minimum spectra also indicate the decrease in noise level with depth. Unlike for the median, the deepest subarray has a consistently lower noise level for all frequencies (DC to half the Nyquist rate).

Using data from 145 hydrophones, Figure 2 shows how the noise levels for 6 different center frequencies vary as a function of depth. The median spectra (left subplot) show a marked decrease with depth below 4500 m for 20 Hz, 50 Hz, and 100 Hz. At 20 Hz, the median noise level for depths

shallower than 2000 m is substantially increased. Again, a large portion of this is likely due to vibration noise from cable strum. At 50 Hz the cable strum appears to affect hydrophones at depths shallower than 1000 m. The minimum spectra (right subplot) show the expected sharp decrease in level below the critical depth. They also show that the minimum noise level for the 6 frequencies decreases towards the surface for depths less than 500 m. This behavior requires further investigation. At present we are not aware of any comparable full water column measurements in the literature, *e.g.*, the CHURCH OPAL experiment focused on depths below 3000 m [5].

Figure 3 shows histograms of the measured noise levels at 50 Hz for the top and bottom hydrophone of each subarray. These statistics were compiled from 487 processed receptions. As might be expected, the shallowest and deepest subarrays show the most difference between the distributions of their top/bottom phones. The shallowest hydrophone (180 m) shows the largest spread. The main part of its distribution is centered at about 75 dB, which is 5 dB lower than the hydrophone at 1178 m, but the noise levels on this hydrophone reach 125 dB occasionally. For the deepest subarray, the top phone (4383 m) has a mean level that is about 6 dB higher than the bottom phone located at 5381 m.

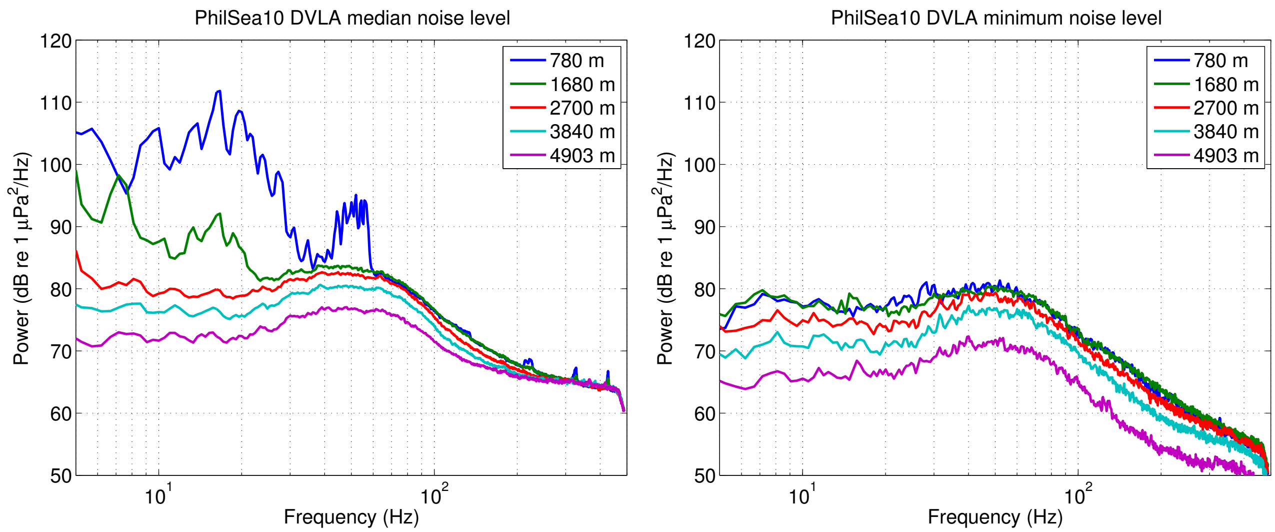
Figures 4 and 5 provide a first look at the vertical directionality measured by the 5 DVLA subarrays. Only the equally-spaced segments of each subarray are processed. (Restricting the initial processing to equally-spaced subarrays is for convenience since it allows efficient processing using a fast Fourier transform implementation.) The sensor spacing for these segments are 20 m, 20 m, 60 m, 60 m, and 40 m, respectively. Note that the data are calibrated, and the spectrum is normalized to provide levels in dB relative to 1 μPa^2 per Hz per rad/m. The results in Figures 4 and 5 show a narrowing of the vertical distribution with depth, similar to that observed in PhilSea09 and observed by Anderson [1]. The figures for the top two subarrays also indicate the presence of an angular component that is particularly strong at low frequency. This component appears in most of the receptions and is likely due to mechanical vibrations of the array, *i.e.*, cable strum. Assuming that this component is a compressional strum mode propagating up and down the array, it has a speed of approximately 3000 m/s.

IMPACT/APPLICATIONS

This project addresses three interesting ocean acoustics topics of relevance to the Navy. The first topic is deep ocean ambient noise. The Philippine Sea experiments provide a unique set of high quality noise measurements that can be used to assess the predicted reduction in power below the conjugate depth and quantify the vertical directionality of the noise. Understanding the ambient noise characteristics is important for the design and implementation of adaptive array processing algorithms. In particular the PhilSea measurements of noise below the critical depth provide essential information for predicting the performance of bottom-mounted arrays.

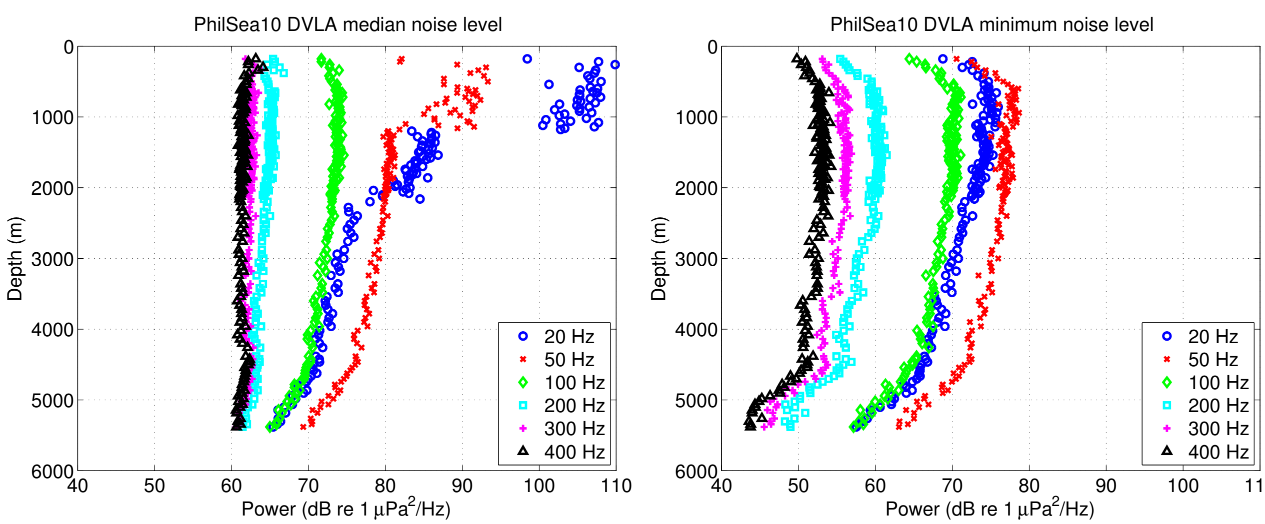
The second topic is mode propagation through environments containing both mesoscale and internal wave processes. Environmental variability induces mode scattering that can have a strong effect on the coherence of both signals and noise. The 150-element vertical line array deployed in the PhilSea provides significantly greater aperture, thus better mode resolving power, than arrays deployed previously. The analysis from this experiment will be valuable in refining statistical propagation models for dynamic environments such as the Philippine Sea.

The third topic of interest is acoustic mode tomography. The low modes provide information about the environment around the deep sound channel axis, which is difficult to obtain with a ray-based inversion.



(a) Median noise spectra (b) Minimum noise spectra

Figure 1: Median and minimum temporal spectra recorded during T6 reception times after YD 305. Spectra are shown for depths of 780 m, 1680 m, 2700 m, 3840 m, and 4903 m (the middle hydrophone of each of the five subarrays.) Statistics were computed from 152 receptions. The plots show the expected decrease in ambient noise level with depth. The median plots indicate the presence of strong cable strum components in the top two subarrays for frequencies up to 60 Hz.



(a) Median noise spectra (b) Minimum noise spectra

Figure 2: Median and minimum temporal spectra as a function of depth recorded during T6 reception times after YD 305. Statistics were computed from 152 receptions. Spectra are shown for 145 hydrophones on the DVLA. Both the median and minimum plots demonstrate the significant decrease in noise levels below the critical depths, as expected. The decrease in the minimum noise level at the shallowest depths requires further investigation.

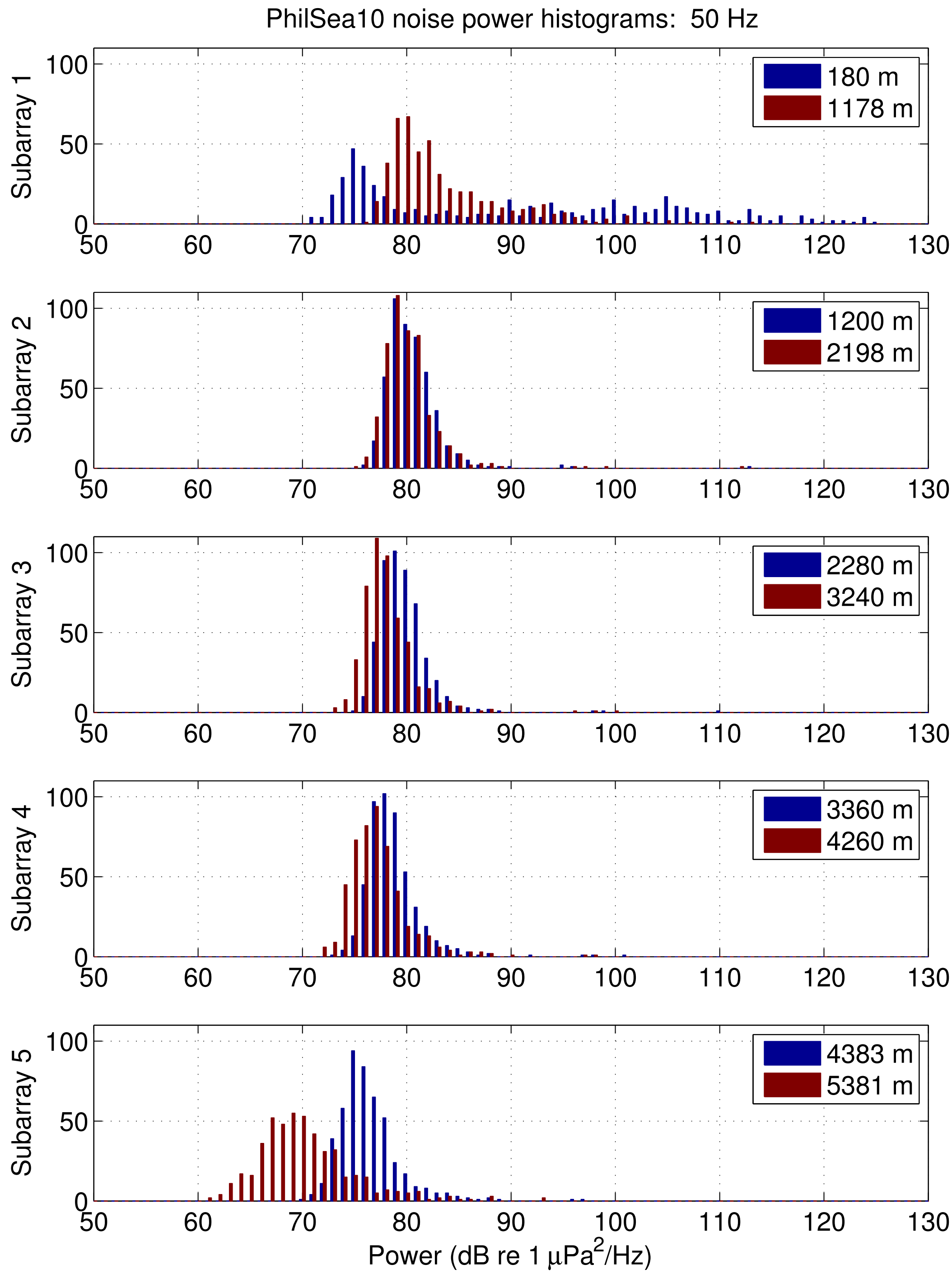
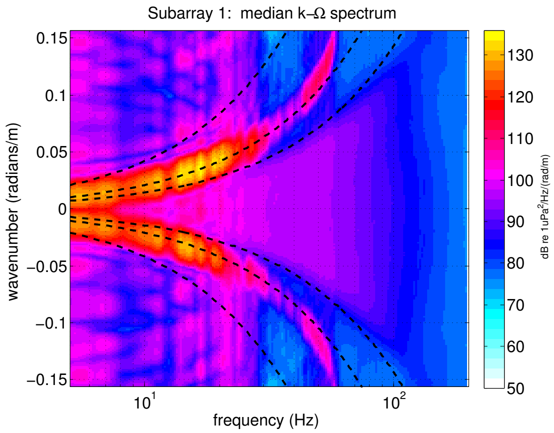
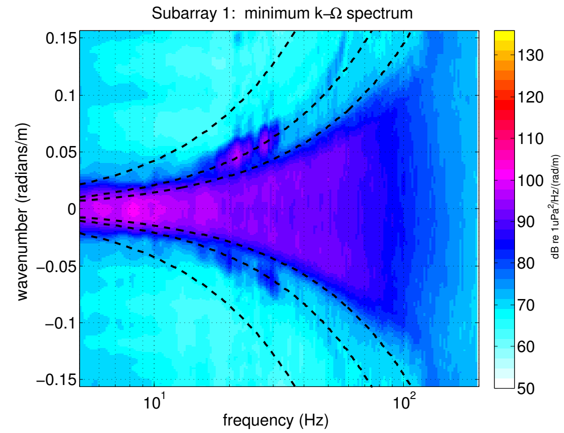


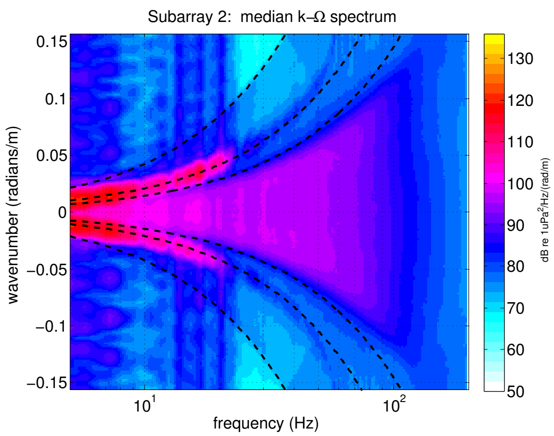
Figure 3: Histograms of noise power at 50 Hz for the top and bottom hydrophone of each of the subarrays in the DVLA. Statistics were computed using 487 receptions spread throughout the year-long experiment. The histograms illustrate the large spread in noise levels for the shallowest subarray, and the decrease in noise levels below the critical depth for the deepest subarray.



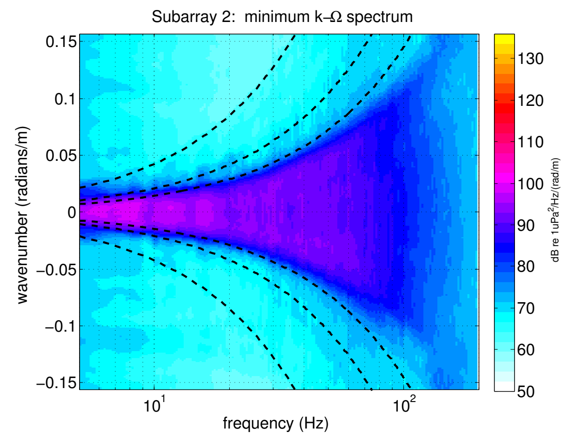
(a) Median spatial spectrum for DVLA subarray 1



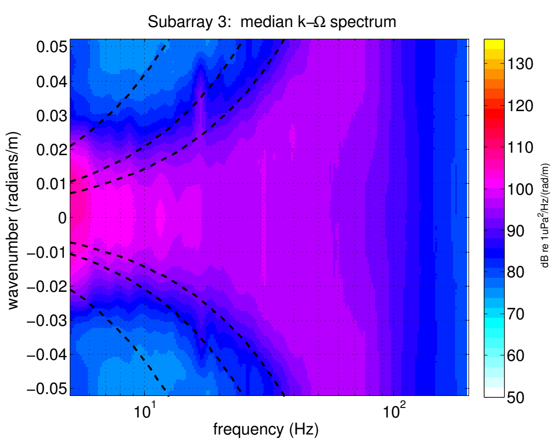
(b) Minimum spatial spectrum for DVLA subarray 1



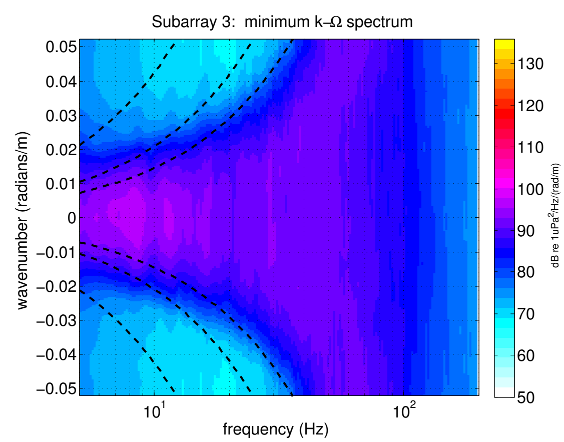
(c) Median spatial spectrum for DVLA subarray 2



(d) Minimum spatial spectrum for DVLA subarray 2

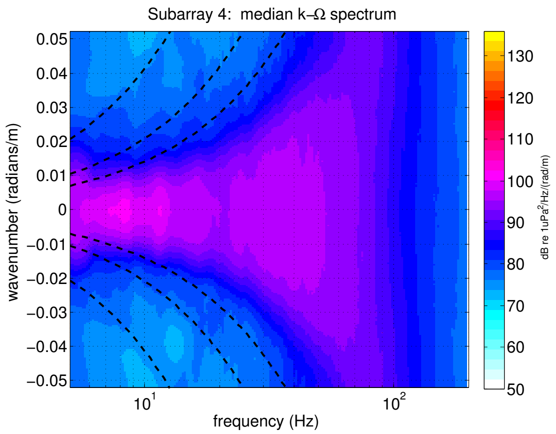


(e) Median spatial spectrum for DVLA subarray 3

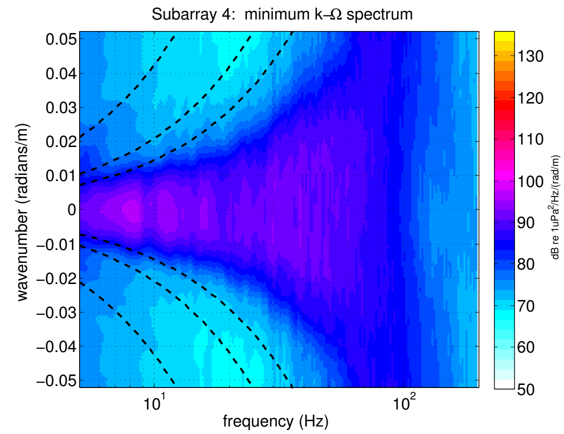


(f) Minimum spatial spectrum for DVLA subarray 3

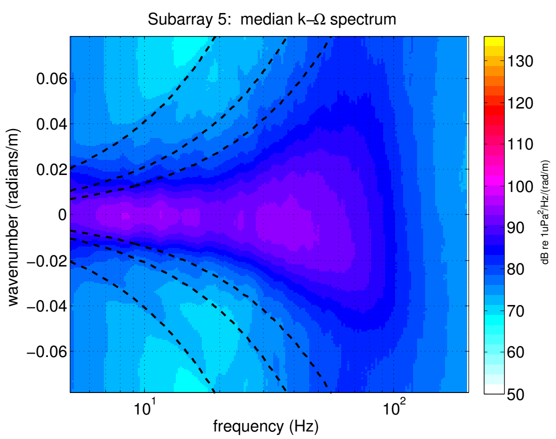
Figure 4: Median and minimum spatial spectra for subarrays 1 through 3 of the PhilSea10 DVLA. The temporal frequency axis is displayed on a log scale. The outer set of dashed lines on the plots marks the boundaries of the visible region (+/- 90 deg), and the inner set denotes +/- 20 deg. The middle set of lines corresponds to +/- 90 deg with a speed of 3000 m/s, which is the speed associated with the strum component. The median plots indicate that cable strum is a prominent feature below 60 Hz for the two uppermost arrays.



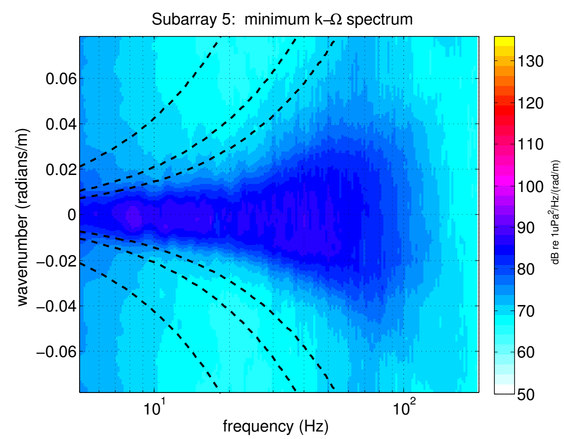
(a) Median spatial spectrum for DVLA subarray 4



(b) Minimum spatial spectrum for DVLA subarray 4



(c) Median spatial spectrum for DVLA subarray 5



(d) Minimum spatial spectrum for DVLA subarray 5

Figure 5: Median and minimum spatial spectra for subarrays 4 and 5 of the PhilSea10 DVLA. The outer set of dashed lines on the plots marks the boundaries of the visible region (+/- 90 deg), and the inner set denotes +/- 20 deg. The middle set of lines corresponds to +/- 90 deg with a speed of 3000 m/s, which is the speed associated with the strum component. These plots illustrate the expected narrowing of the vertical distribution for the deeper subarrays.

In addition to standard tomography using controlled sources, this project is investigating inversions based on ambient noise. These offer the possibility that a processor could be "tuned" to the environment using an automated noise analysis procedure, providing improved performance without requiring additional sensors (such as thermistors) on the receiving array.

RELATED PROJECTS

The initial work on empirical mode estimation was funded by ONR Award N00014-05-1-0639 in 2006-2008. This work is related to ONR Award N00014-06-1-0223, an ONR Graduate Traineeship that funded Tarun K. Chandrayadula. Dr. Chandrayadula graduated in January 2010 and is now a postdoctoral fellow at the Naval Postgraduate School. The Philippine Sea experiments involved researchers from a number of institutions. In addition to the six tomography sources installed by Peter Worcester's group, there were ship-suspended sources deployed by James Mercer (APL-UW), Gerald D'Spain (SIO), and Arthur Baggeroer (MIT)/Kevin Heaney (OASIS). This project focuses only on the receptions for the six tomography sources and the 2009 designated noise receptions; the continuous recording periods for the ship-suspended sources are not being processed. John Colosi (NPS) was responsible for a number of the environmental measurements included in the PhilSea experiments. The PI is collaborating with Peter Worcester and Matthew Dzieciuch (SIO) on the analysis of the Philippine Sea data set.

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HONORS/AWARDS/PRIZES

Professor Kathleen Wage (George Mason University) was one of 53 participants invited by the National Academy of Engineering to the Frontiers of Engineering Education Symposium in December 2010.